NAVWEPS REPORT 7628
Part 3
NOTS TP 3229
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STUDIES OF A VENTILATED SUPERCAVITATING PROPELLER ON A TORPEDO TEST VEHICLE

PART 3. WATER-TUNNEL AND FINAL CABLEWAY TESTS, AND OVER-ALL SUMMARY OF THE PROJECT

by

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ABSTRACT. A full-scale torpedo test vehicle equipped with a ventilated supercavitating propeller was studied in the Garfield Thomas Water Tunnel at the Pennsylvania State University to obtain performance information and observe details of ventilation flow. A peak efficiency of 70% was obtained near the operating advance ratio. Visual observations indicated improper ventilation of the propeller cavity. However, subsequent runs on the underwater cableway with the modified propeller gave improved acoustic results.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

June 1963

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

This report concludes the work on a ventilated supercavitating propeller sponsored by the Office of Naval Research under ONR Task No. NR-062-224 entitled "Ventilated Propellers." The research was begun in 1959 and the final tests were completed in 1962. During this period, and as a direct result of this project, a number of additional problems in ventilated flows were investigated at this Station, under sponsorship of other activities.

First test results were presented in NAVWEPS Report 7628, Parts 1 and 2 (1961). This third part of the report gives additional data and a general summary of the entire project. Portions of the work reported here were presented at the Ninth International Towing Tank Conference, Paris, 1960; the Fourth Symposium on Naval Hydrodynamics, Washington, 1962; and the 17th Annual Meeting of the American Rocket Society, Los Angeles, 1962.

Review of this report for technical accuracy was performed by T. G. Lang and K. E. Smith of this Station.

Released by
D. J. WILCOX, Head,
Underwater Ordnance Dept.
14 May 1963

Under the authority of
WM. B. McLEAN
Technical Director

NOTS Technical Publication 3229
NAVWEPS Report 7628, Part 3

Published by .... Underwater Ordnance Department
Manuscript 807/MS-147
Collation .... Cover, 9 leaves, abstract cards
First printing .... 155 numbered copies
Security classification .... UNCLASSIFIED

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INTRODUCTION

If a gas is admitted to the vapor cavity of a supercavitating propeller, the propeller is said to be ventilated. The effective cavitation number of the propeller is thus reduced, allowing supercavitation to extend over a lower speed range or to a greater depth. Because of the cushioning effect of the gas, radiated noise is also generally reduced, as well as cavitation erosion caused by portions of the cavity collapsing on the blade surface. Early experiments (Ref. 1 and 2) indicated the feasibility of putting this type of ventilation to practical use.

This report augments previous results (Ref. 3 and 4) obtained with a ventilated supercavitating propeller designed to operate in the wake of a body of revolution 15 inches in diameter and about 120 inches long. The experiments were conducted on the underwater cableway of the Naval Ordnance Test Station (NOTS) and in the Garfield Thomas Water Tunnel of the Ordnance Research Laboratory (ORL).

The propeller was designed by the David Taylor Model Basin to operate in the wake of an existing cableway test vehicle. Design conditions were 65 knots forward speed, 7,500 rpm, and a thrust of 1,341 pounds at 70% propeller efficiency. Propeller diameter is 11 inches, giving a design advance ratio, $J = V/nD$, of 0.96. Two views of the propeller are given in Fig. 1. The blade sections are of the Tulin type, modified by the addition of two drilled holes for ventilation gas on the upper, or suction, surface of each blade. One hole can be seen near the blade root; the other terminates in a slot extending over the outer region of the blade. All ventilation holes communicate to the hub of the propeller.

WATER-TUNNEL TESTS AND RESULTS

To obtain further information on the performance of the propeller, the full-scale vehicle was placed in the Garfield Thomas Water Tunnel, a 48-inch-diameter tunnel with provision for gas removal by a vacuum-pump system. The working section of the tunnel was fitted with a contoured liner to approximate open-flow streamlines at the tunnel wall. The turbine drive of the cableway vehicle was replaced by a calibrated electric motor and air was piped into the propeller through the support strut of the vehicle. The external size and contour of the test vehicle was identical to the regular cableway configuration except that the cableway attachment struts were removed. Before test data were taken, the velocity profile just forward of the propeller was adjusted, by means of empirical roughness additions, to the velocity profile measured at the same location during the cableway tests.

FIG. 1. Two Views of the Ventilated Supercavitating Propeller.

Data were taken over a range of advance ratios from 0.85 to 1.20 at cavitation numbers, σ_v (based on the vapor pressure of the water), which ranged from about 0.45 to 1.35. The tunnel was operated at a working-section velocity of 35 ft/sec and air was discharged through the propeller ventilation holes at rates from 0.0 to about 7.0 cfm at standard temperature and pressure (STP).

Figure 2 is a plot of efficiency, η, torque coefficient, K_Q, and thrust coefficient, K_T, as functions of advance ratio, J, for the propeller without airflow, i.e., as a supercavitating propeller, The various parameters are defined as follows:

$$K_Q = \frac{Q}{(\rho/g)n^2D^5}$$

$$K_T = \frac{T}{(\rho/g)n^2D^4}$$

$$\eta = \frac{K_T J}{K_Q 2\pi}$$

$$J = \frac{V}{nD}$$

$$\sigma_v = \frac{P_{local} - P_{vapor}}{1/2(\rho/g)V^2}$$

where

Q = torque

ρ = density of fluid

n = propeller rotative speed

D = propeller diameter

T = thrust of propeller

V = forward velocity or free-stream velocity

P_{local} = local free-stream static pressure

P_{vapor} = vapor pressure of water

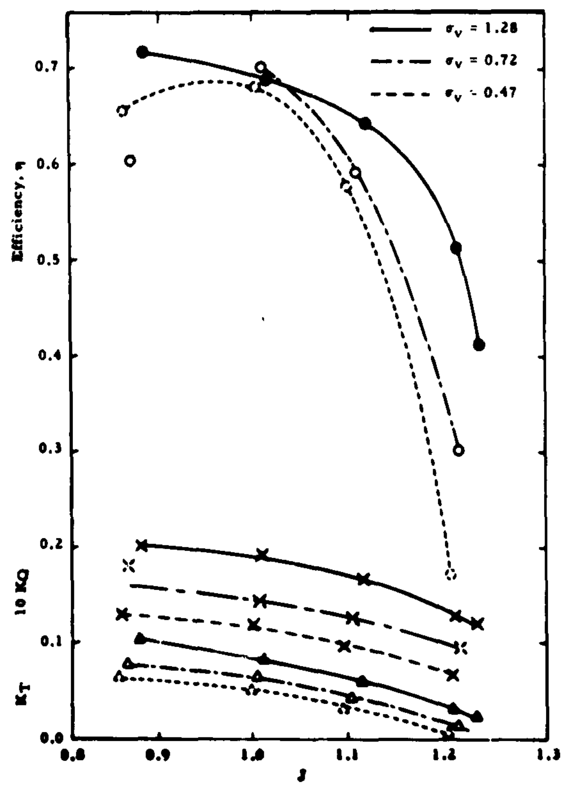

FIG. 2. Performance of the Propeller Without Ventilation.

At the design J of 0.96, efficiency appears to maximize near the design value of 70% for the three values of σ_V tested. However, the character of the flow changes as J is increased from 0.85 to 1.0, as shown by Fig. 3 and 4. Figure 3 shows the cavity starting from the leading edge of the propeller, as is typical in supercavitating operation, with J = 0.85. The situation when J is increased to 1.0 is shown in Fig. 4, and it can be seen that the point of cavity formation has moved back to the ventilation slot. At this J, the propeller could not be made to cavitate from the leading edge of the blade, even at the lowest σ_V tested.

This change in the flow pattern has important effects as air is introduced into the propeller. Figure 5 shows that the performance at J = 0.85 falls off as the airflow parameter, Q', is increased. Torque and thrust coefficients appear to approach a constant value as Q' is further increased, indicating that efficiency curves will also approach a constant value. The decrease in efficiency is probably due to the influence of friction on the wetted pressure face of the propeller blades. In potential-flow theory, ventilation should reduce both lift and drag

FIG. 3. Supercavitating Propeller Operating With J = 0.85 and No Airflow.

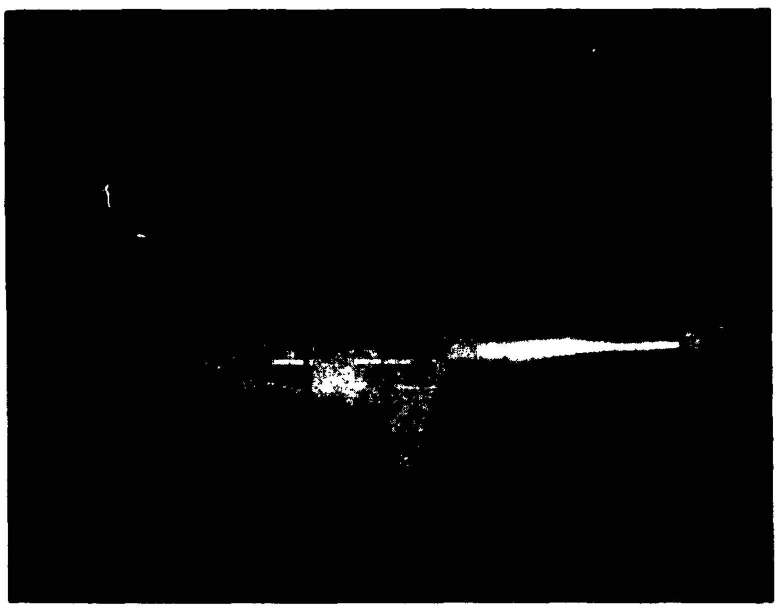

FIG. 4. Supercavitating Propeller Operating With J = 1.00 and No Airflow.

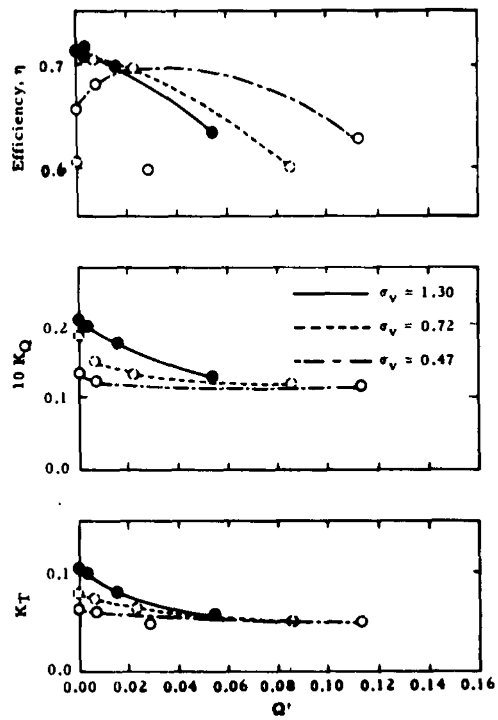

FIG. 5. Effect of Airflow on Performance of Ventilated Supercavitating Propeller at J = 0.85.

coefficients (C_L and C_D) of a blade section, but their ratio should remain constant. The friction coefficient (C_f) is unchanged by ventilation. Thus the Lift/Drag ratio $\cong C_L/(C_D + C_f)$ of the blade section decreases, lowering propeller efficiency.

The airflow parameter is defined as

$$Q' = \frac{14.7}{P_{local}} \times \frac{Q_{STP}}{ZA_B\sqrt{V^2 + (2\pi r_c n)^2}}$$

where

Q_{STP} = airflow rate, STP
Z = number of blades
A_B = base area of each blade
r_c = radius of centroid of A_B

Q' may be thought of as the ratio of the local gas flow to the volume swept out by the blunt bases or trailing edges of the propeller blades as they move through the water. As a comparison, values of Q' ranging from 0.0 to about 0.075 were measured at the 50-foot depth during the runs on the underwater cableway.[1]

At J = 1.0, the addition of air causes immediate reduction of the efficiency,[2] as shown in Fig. 6. The difference between behavior at

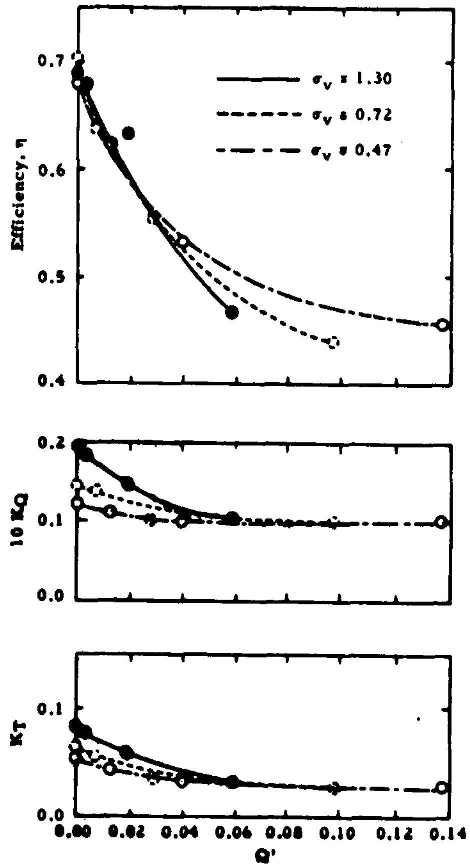

FIG. 6. Effect of Airflow on Propeller Performance at J = 1.0.

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[1] Values of blade-filling ratio, R_Q, reported in Ref. 3 have been discovered to be incorrect due to arithmetic error. The trends are proper, but the values of blade-filling ratio reported there are high by an approximate factor of 2. Q' is simply the previously used R_Q times a pressure correction.

[2] This change in efficiency was not noticed in the previous cableway tests (Ref. 3), possibly due to masking by instrumentation inaccuracy.

J = 0.85 and at J = 1.0 is believed to be the result of the difference in cavity attachment-point location and the occurrence of some pressure-face ventilation. Figures 7 and 8 compare the ventilated cavity appearance for the two J conditions. Strong ventilation ($Q' \cong 0.10$) would not force the cavity forward to the leading edge when J = 1.0. Pressure-face ventilation is barely detectable in Fig. 8. Pressure-face cavitation was noticed at all higher J values, and it is probable that separation occurs above J = 1.0. Strong ventilation would tend to flow around the blade tip into the separated region.

The water-tunnel tests also shed light on another problem observed during earlier cableway tests. Song and Silberman (Ref. 5) had shown experimentally that ventilation reduces the radiated noise of cavities produced by simple bodies over a wide range of frequencies. However, ventilation of this supercavitating propeller reduced the radiated noise of the cableway test dynamometer only in the higher frequencies. At frequencies below 1 kc, the radiated noise actually increased with increased ventilation. The water-tunnel photographs offer a partial explanation. Figure 9 shows the propeller in operation at J = 1.07 and Q' = 0.22, i.e., very heavy ventilation. The hole at the root of the propeller blade is seen to vent directly into solid water, and pulsations appear on the surface of the air cavity. Calculations indicate that the low-frequency noise measured during the cableway tests (Ref. 4) may be attributable to this source.

These observations inspired the decision to operate the propeller on the underwater cableway again, with the root-ventilation hole closed, to determine experimentally whether the ventilation method was the source of the low-frequency noise previously observed in the cableway runs.

UNDERWATER CABLEWAY TESTS

The Underwater Cableway Facility (Ref. 6) at Morris Dam, near Azusa, Calif., consists of a pair of steel cables stretched under the surface of a lake to form a path about 1,000 yards long, with a maximum depth of about 60 feet. Figure 10 depicts the general cableway concept. Internal instrumentation in the dynamometer vehicle gives temperature, pressure, and forward speed information; external hydrophones are arranged to study the radiated noise of the vehicle. Figure 11 shows the ventilated-propeller vehicle attached to the cables before being submerged for a test run.

A sketch of the dynamometer vehicle is shown in Fig. 12. A turbine operating on decomposed hydrogen peroxide drives the propeller; the gaseous exhaust products from the turbine then pass down the propeller shaft and into the propeller. A meter in the hub allows gas to be admitted into the propeller at various rates; the remaining gas is discharged axially from the propeller hub.

FIG. 7. Ventilated Supercavitating Propeller, J = 0.85, Q' = 0.112.

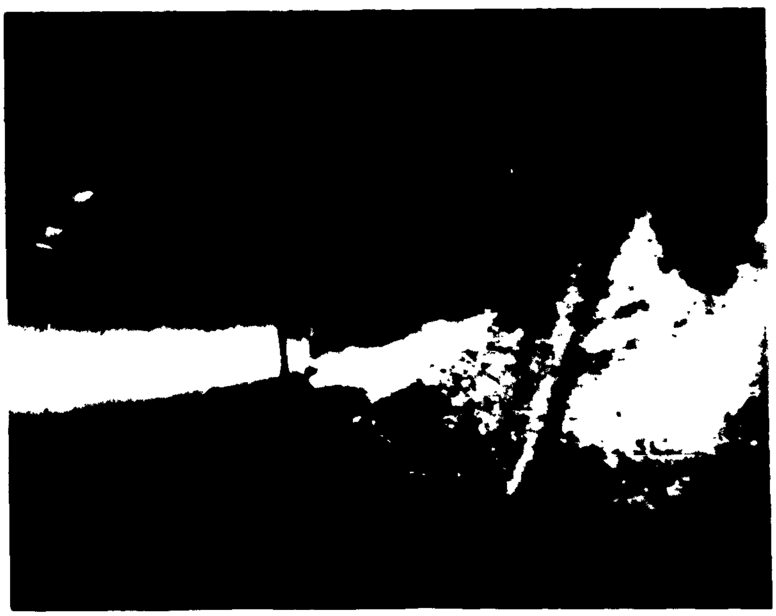

FIG. 8. Ventilated Supercavitating Propeller, J = 1.00, Q' = 0.0745.

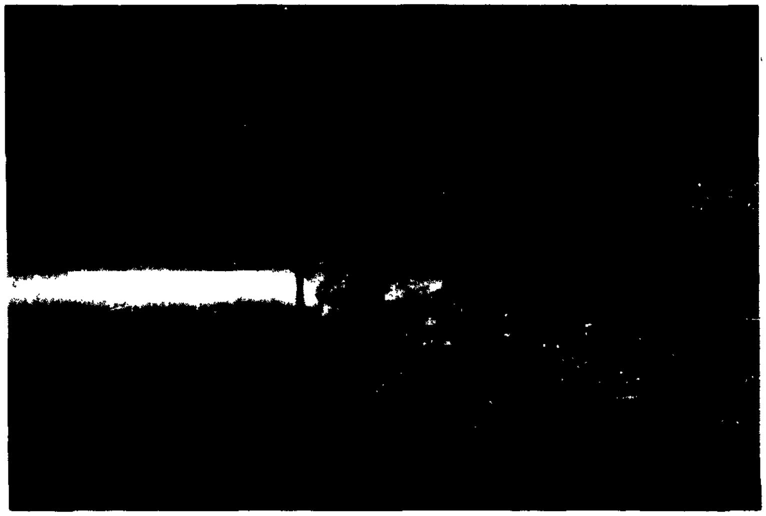

FIG. 9. Ventilated Supercavitating Propeller,
J = 1.07, Q' = 0.22.

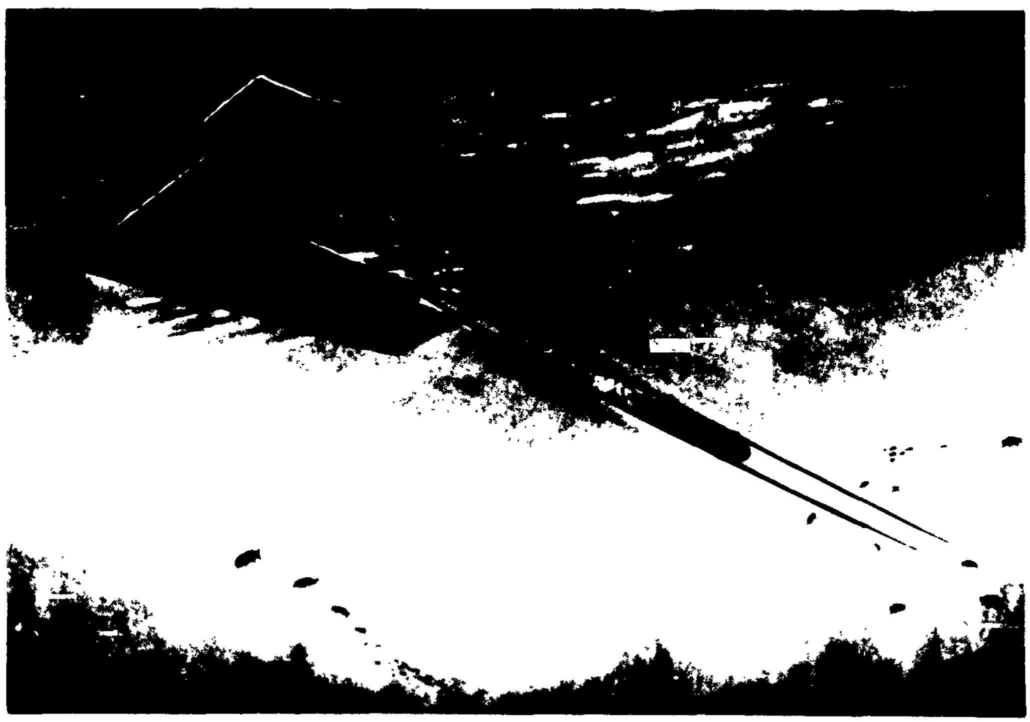

FIG. 10. Artist's Sketch of Dynamometer Operating on Underwater Cableway. Launching barge at upper left.

FIG. 11. Dynamometer Vehicle With Ventilated Propeller Mounted on Cableway.

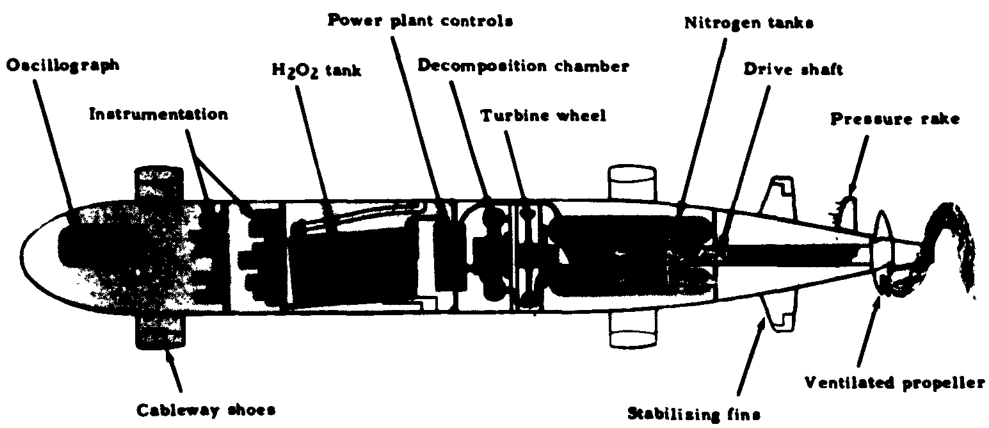

FIG. 12. Cutaway View of Cableway Dynamometer Vehicle.

In addition to the original series of tests reported in Ref. 3, three more runs were made, as nearly identical to the previous runs as possible, except that the root-ventilation holes on the propeller were blocked. These tests were intended principally to measure the radiated noise with the modified propeller and were made at 39.9, 41.6, and 45.0 knots at the 50-foot depth point on the cableway. Advance ratios of 0.99, 1.00, and 1.032, respectively, were recorded. This progressive increase in J was obtained by reducing the gas-flow rate through the propeller. As demonstrated in Ref. 3, varying the gas-flow rate results in large changes in J in this ventilated propeller at constant operating depth. Values of Q'_{side} of 0.0274, 0.0212, and 0.0172, respectively, were measured in this series of tests.[3]

Blocking of the root-ventilation hole did not significantly change the propulsion characteristics or horsepower input to the propeller (90, 99, and 118 hp, respectively) compared with the previous cableway tests.

However, major changes in the radiated noise output of the vehicle were observed. Table 1 gives the test conditions and Table 2 compares the acoustic results at several discrete frequencies for two runs on the underwater cableway at nearly identical forward speeds and gas-flow parameters through the side venting hole, Q'_{side}. The tests differ only in that one (Run 6, Ref. 3) utilized the propeller as originally designed; the other employed the modified propeller. The acoustic data are presented as db changes in radiated noise output from the output measured from the vehicle with the propeller operating without ventilation, i.e., as a supercavitating propeller. As shown in the left column of Table 2, ventilation of the unmodified propeller reduced the high-frequency noise output but raised that of the low-frequency noise.

TABLE 1. Test Conditions for Propeller Noise-Level Investigations

Parameter	Full Ventilation	Side Ventilation Only
Forward speed, knots	41.5	41.6
Q', total	0.0739	0.0212
Q', side	0.0228	0.0212
Q', root	0.0511	0.0000

[3] The term Q'_{side} refers to the gas-flow parameter, taking into account only gas flowing through the side ventilation holes of the propeller.

TABLE 2. Change in Radiated-Noise Level From Non-Ventilated Condition

Frequency, cps	Change in Db Levels	
	Full Ventilation	Side Ventilation Only
300	+8.5	-1.0
500	+11.0	+4.7
1,000	+4.3	-5.7
1,500	0.0	-10.6
2,000	0.0	-8.5
3,000	-7.1	-12.0
5,000	-12.5	-20.0
10,000	-10.7	-13.9
20,000	-13.3	-13.6

It was surmised from the water-tunnel tests that the increased low-frequency noise output was brought about because the hub-ventilation hole directed the gas into solid water instead of into the blade cavity. The data column at the right of Table 2 shows that this was the case. The modified-propeller noise output was from 5 to 10 db less than the original design at all but the highest frequencies. The ventilated modified propeller was quieter than the non-vented at all frequencies except 500 cps. The absolute noise level of this propeller compares favorably with any propulsor tested on the underwater cableway.

SUMMARY OF THE PROJECT

During the period from 1959 to 1962, 16 tests were made on the underwater cableway with an experimental torpedo fitted with a super-cavitating propeller ventilated with exhaust gas from the test vehicle power plant. These tests, at speeds from 40 to 60 knots, showed the effects of ventilation gas-flow rate and depth of operation on propeller performance. Design goals of propeller efficiency and advance ratio were closely met in the non-ventilated condition. While ventilation caused a marked decrease in propeller efficiency, the acoustic measurements made with the propeller in its final ventilated modification indicated a reduction of radiated noise at almost all frequencies, compared with the underwater noise produced by the unventilated propeller.

In addition, the full-scale vehicle was tested in the Garfield Thomas Water Tunnel. These studies allowed propeller performance to be evaluated with considerable precision. Visual inspection of the ventilated propeller in action led to the modifications that produced low radiated noise in subsequent cableway tests.

TECHNOLOGICAL CONTRIBUTIONS

A number of important advances achieved in this project are believed to have been made for the first time.

1. A ventilated propeller was used to propel a marine vehicle.
2. A gas other than air was used for propeller ventilation.
3. A supercavitating propeller was used to propel a torpedo-type vehicle.
4. A ventilated propeller was tested in a water tunnel.

In addition, the usefulness of the underwater cableway (Ref. 6 and 7) as a unique facility for testing ventilated-flow devices was demonstrated.

CONCLUSIONS

The following conclusions are drawn from this work.

1. The variation of advance ratio with gas-flow rate and depth, as well as the very fact of a gaseous wake, restricts the application of a ventilated supercavitating propeller to specialized uses in underwater ordnance. The most important use now foreseen will be the application to high-speed boats, especially in the military field, where quiet operation is desirable.

2. The goals of high rotative speed and quiet operation at high forward speed were achieved, with good propulsive efficiency. These achievements indicate application to turbine-driven hydrofoil craft.

3. The success of this type of propeller has stimulated research into gas-water flows in propeller design (Ref. 8 and 9), leading to further improvements through the use of different blade sections.

RECOMMENDATION FOR FURTHER WORK

The open-water characterization of this propeller in a towing tank would further add to the understanding of the propeller's performance.

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ACKNOWLEDGMENT

The ventilated supercavitating propeller was designed and fabricated at the David Taylor Model Basin. Special appreciation is due the staff of the Garfield Thomas Water Tunnel for their skillful conduct of many of the tests.

NEGATIVE NUMBERS OF ILLUSTRATIONS

Fig. 1, LHL-P 30305 and 30304; Fig. 2, LHL-P 24369; Fig. 3, LHL-P 24343-3; Fig. 4, LHL-P 24343-2; Fig. 5, LHL-P 24369; Fig. 6, LHL-P 24369; Fig. 7, LHL-P 24343-1; Fig. 8, none; Fig. 9, LHL-P 24343-4; Fig. 10, LHL-P 22456; Fig. 11, LHL-P 24406; Fig. 12, LHL-P 22455.

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Studies of a Ventilated Supercavitating Propeller on a Torpedo Test Vehicle. Part 3. Water-Tunnel and Final Cableway Tests, and Over-All Summary of the Project, by J. W. Hoyt. China Lake, Calif., NOTS, June 1963. 18 pp. (NAVWEPS Report 7628, Part 3, NOTS TP 3229), UNCLASSIFIED.

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NAVWEPS Report 7628
Part 3

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